

PRELIMINARY RESULTS OF PERFORMANCE MEASUREMENTS ON A CYLINDRICAL HALL-EFFECT THRUSTER WITH MAGNETIC FIELD GENERATED BY PERMANENT MAGNETS

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ABSTRACT

The performance of a low-power cylindrical Hall thruster, which more readily lends itself to miniaturization and low-power operation than a conventional (annular) Hall thruster, was measured using a planar plasma probe and a thrust stand. The field in the cylindrical thruster was produced using permanent magnets, promising a power reduction over previous cylindrical thruster iterations that employed electromagnets to generate the required magnetic field topology. Two sets of ring-shaped permanent magnets are used, and two different field configurations can be produced by reorienting the poles of one magnet relative to the other. A plasma probe measuring ion flux in the plume is used to estimate the current utilization for the two magnetic configurations. The measurements indicate that electron transport is impeded much more effectively in one configuration, implying a higher thrust efficiency. Preliminary thruster performance measurements on this configuration were obtained over a power range of 100-250 W. The thrust levels over this power range were 3.5-6.5 mN, with anode efficiencies and specific impulses spanning 14-19% and 875-1425 s, respectively. The magnetic field in the thruster was lower for the thrust measurements than the plasma probe measurements due to heating and weakening of the permanent magnets, reducing the maximum field strength from 2 kG to roughly 750-800 G. The discharge current levels observed during thrust stand testing were anomalously high compared to those levels measured in previous experiments with this thruster.

I. INTRODUCTION

While annular Hall thrusters can operate at high efficiency at kW power levels, it is difficult to construct one that operates over a broad envelope from ~1 kW down to ~100 W while maintaining an efficiency of 45-55%. Scaling to low power while holding the main dimensionless parameters constant requires a decrease in the thruster channel size and an increase in the magnetic field strength [1,2]. Increasing the magnetic field becomes technically challenging since the field can saturate the miniaturized inner components of the magnetic circuit and scaling down the magnetic circuit leaves very little room for magnetic pole pieces and heat shields. In addition, the central magnetic pole piece defining the interior wall of the annular channel can experience excessive heat loads in a miniaturized Hall thruster, with the temperature eventually exceeding the Curie temperature of the material [2] and in extreme circumstances leading to accelerated erosion of the channel wall.

An alternative approach is to employ a cylindrical Hall thruster (CHT) geometry [3]. Laboratory model CHTs have operated at power levels ranging from ~50 W up to ~1 kW. These thrusters exhibit performance characteristics that are comparable to conventional, annular Hall thrusters of similar size. Compared to the annular Hall thruster, the CHT's insulator surface area to discharge chamber volume ratio is lower. Consequently, there is the potential for reduced wall losses in the channel of a CHT, and any reduction in wall losses should translate into lower channel heating rates and reduced erosion, making the CHT geometry promising for low-power applications. This potential for high performance in the low-power regime has served as the impetus for research and development efforts aimed at understanding and improving CHT performance [3-7].

In this paper, we present preliminary results from tests performed with a CHT that uses permanent magnets to produce the magnetic field topology. This thruster has the promise of reduced overall power consumption over previous CHT iterations that employed electromagnets. Beam current data are presented to show the effect of the magnetic field topology on the plume profile and current utilization. Thruster performance measurements (thrust, I_{sp} , and anode efficiency) obtained using a thrust stand are presented to evaluate against previous electromagnet CHT performance levels and also to provide a baseline against which future iterations of the permanent magnet CHT may be compared.

The outline for the rest of this paper is as follows. In Section II the thruster and test apparatus are described.

Data from the testing are presented in Section III. A discussion of the data and difficulties experienced during testing is located in Section IV.

II. EXPERIMENTAL APPARATUS

Tests were conducted on a cylindrical Hall thruster at both the Princeton Plasma Physics Laboratory (PPPL) and NASA's Marshall Space Flight Center (MSFC). We proceed first with a description of the thruster and then discuss the facilities at both PPPL and MSFC that were used to test the CHT.

A. CYLINDRICAL HALL THRUSTER WITH PERMANENT MAGNETS

Measurements were obtained using the 2.6 cm channel diameter permanent magnet PPPL CHT shown in Fig. 1. The thruster is roughly 5.5 cm in overall diameter and 3.5 cm long, massing roughly 350 g. The thruster channel is comprised of a ceramic boron-nitride insulator with propellant fed from an annular anode. Two sets of samarium-cobalt (Sm-Co) rare-Earth magnets are used to produce the magnetic field. The magnets can be oriented in the same direction to produce the 'direct' magnetic field topology shown in Fig. 2A, or they can be oriented to oppose each other producing the 'cusp' field configuration in Fig. 2B. The magnetic field in the plume region is roughly the same for either permanent magnet configuration, but the field strength is

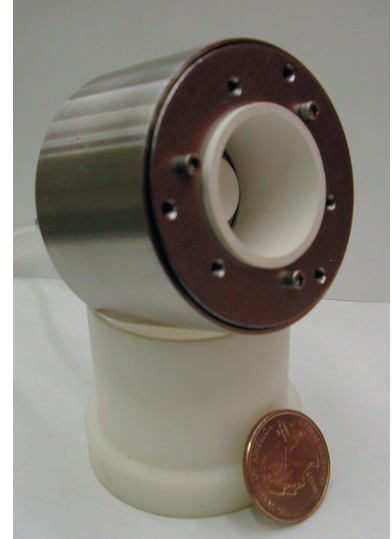


FIG. 1: Laboratory model 2.6 cm CHT with Sm-Co permanent magnets (with US quarter for scale).

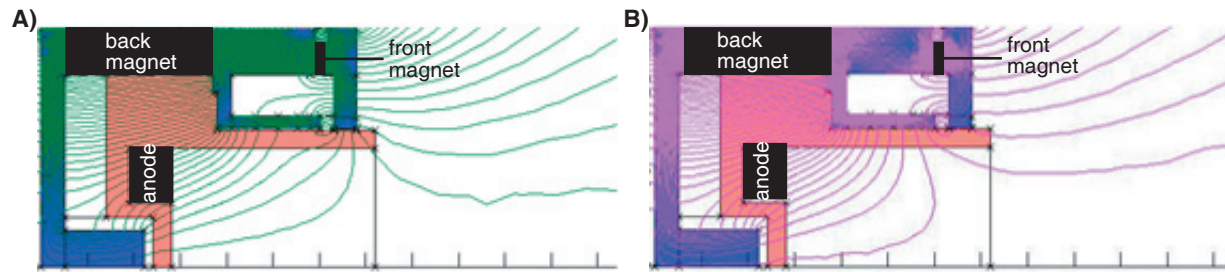


FIG. 2: Magnetic field topology in a laboratory model 2.6 cm CHT with Sm-Co permanent magnets where the magnets are oriented in A) a direct-field alignment and B) a cusp-field alignment. The maximum magnetic field is roughly 2 kG at the axis near the back wall.

greater in the direct-field configuration. There are also differences in the topology inside the thruster channel, with a greater axial component in the direct-field configuration. The maximum field strength inside the thruster channel in either configuration is roughly 2 kG.

The working propellant for all experiments is research-grade xenon gas, and the cathode and anode flow rates are independently controlled. A commercial HeatWave Labs HWPES-250 hollow cathode is used in these experiments, serving as both the thruster cathode and the beam neutralizer.

B. PRINCETON TEST FACILITY

Testing at Princeton was conducted in the PPPL large Hall thruster facility [8]. The vacuum vessel has a volume of 28 m³ and is equipped with cryopumps that maintain the background pressure at a level that does not exceed 3x10⁻⁶ torr. The angular ion flux distribution in the plume was measured using a 2.54 cm planar plume probe with guarding rings like the type described in Refs. [9,10]. The probe is located 70 cm from the thruster and can be rotated through an angle of ± 90 degrees relative to the thruster axis.

C. NASA-MSFC TEST FACILITY

Testing at NASA-MSFC was conducted in a 2.75-m diameter, 7.6-m long stainless steel vacuum chamber. Previous testing of a PPPL CHT was also performed in this facility [6]. The vacuum level inside the chamber is maintained by two 9500 l/s gaseous helium cryopumps. The base pressure of the facility was 2x10⁻⁷ torr, and the pressure level during testing was roughly 1x10⁻⁵ torr.

The propellant flow rate to both the cathode and anode were controlled using two variable 10-sccm MKS 1479 precision flow controllers (calibrated on Xe and controllable to ± 0.1 sccm). All testing was performed with a cathode flow rate of 2 sccm.

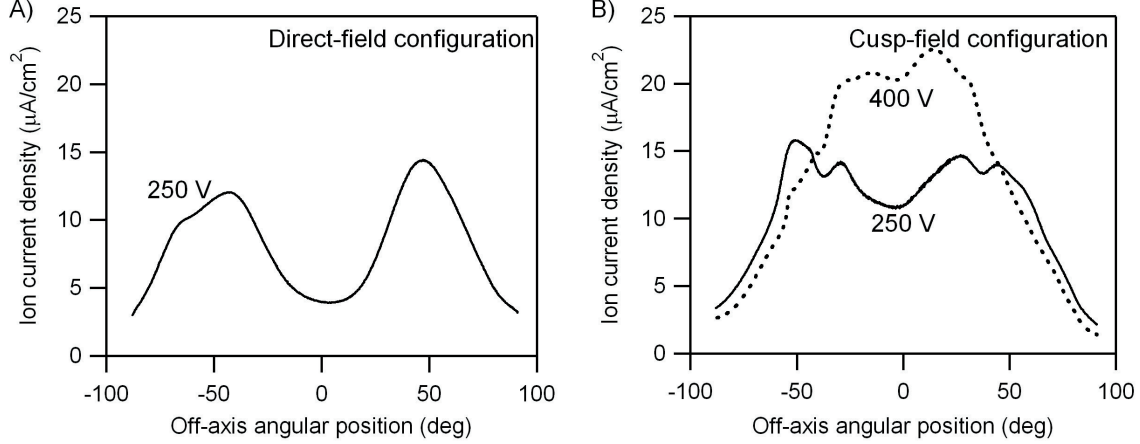


FIG. 3: Planar plume probe measurements showing the ion flux distribution in the CHT beam as a function of off-axis angular position for A) the direct-field configuration and B) the cusp-field configuration. The voltages given for each data set represent the thruster discharge voltages. The anode flow rate for all plume measurements was 4 sccm.

TABLE 1: Summary of discharge and beam current data and current utilization for the direct and cusp-field configurations. The anode flow rate was 4 sccm.

Condition	Discharge Current I_d (A)	Ion Beam Current I_i (A)	Current Util. I_i/I_d
Direct, 250 V	0.35	0.24	0.69
Cusp, 250 V	0.59	0.28	0.47
Cusp, 400 V	0.56	0.30	0.54

Thrust was measured using the variable-amplitude hanging pendulum with extended range (VAH-PER) thrust stand [11]. The stand employs a unique linkage mechanism to convert horizontal deflection of the pendulum arm into amplified vertical deflection of a secondary beam. Displacement (thrust) calibration of the VAH-PER thrust stand is accomplished using an in situ calibration rig that applies a series of known loads

normal to the pendulum arm. Calibration can be performed before, during, and after thruster operation. The measured displacement of the vertically deflecting linkage is recorded as the calibration loads are applied to the arm. Assuming that the relationship between the applied force and the measured displacement is linear allows for a linear curve fit of the calibration data.

III. EXPERIMENTAL DATA

Data from testing conducted with the permanent-magnet CHT are presented in this section. Beam ion current density measurements obtained at PPPL are presented first and followed by performance measurements performed at NASA-MSFC.

A. ION CURRENT DENSITY

The plasma beam current measurements for both the direct and cusp magnetic field configurations with an anode flow rate of 4 sccm are presented in Fig. 3. The beam current density in the direct-field configuration (Fig. 3A) is smaller than the current density in the cusp-field configuration (Fig. 3B). In addition, the ion flux near the centerline in the cusp-field configuration is increased when the thruster discharge voltage is increased from 250 V to 400 V. The thruster discharge current I_d and measured ion beam current I_i are summarized in Table I for each of the magnetic field configuration/discharge voltage combinations tested. The current utilization I_i/I_d for each case is also calculated in the table.

B. THRUSTER PERFORMANCE

Thrust, anode efficiency, and specific impulse (I_{sp}) measurements obtained for the direct-field configuration CHT are presented in Fig. 4. Anode efficiency and I_{sp} (specifically, anode I_{sp}) are computed according to their standard definitions [12] using the measured thrust level, the anode mass flow rate, and the power supply current and voltage readings.

The data presented correspond to three sets of thrust measurements at anode mass flow rates of 4.4, 4.8, and 5.0 sccm. The data span a range from 100 to 250 W in discharge power and show thrust levels from 3.5 to 6.5 mN, anode efficiencies between 14 and 19%, and I_{sp} levels between 875 and 1425 s.

IV. DISCUSSION

Before discussing the data, it must be noted that there were differences in thruster operation at PPPL and MSFC. During thruster conditioning at MSFC, the thruster experienced anomalous heating that, we believe, led to a decrease in the Sm-Co magnetic field strength. After this heating, the maximum magnetic field on the thruster centerline was reduced to 750-800 G.

Even in this reduced field state, the thruster operating at PPPL at specified voltage points and anode flow rates had discharge current levels that were similar to the levels measured for the higher magnetic field strength. In the MSFC setup, these discharge current levels were not achieved at any time. The discharge current was markedly higher than in the PPPL setup and was unstable, oscillating between a lower-current and a higher-current level at many operating points. The 'lower'-current levels measured during oscillating operation were still greater than those measured in the PPPL setup. The information presented in Fig. 4 represents only those data that did not exhibit oscillations during operation. The current drawn by the thruster in even these data sets was significantly greater (by at least 25-30%) than the current measured in the PPPL setup. At present this discrepancy is not well understood.

The cusp-field configuration ion beam current plume measurements shown in Fig. 3B exhibit a greater ion flux along the centerline as the discharge voltage is increased from 250 to 400 V. A comparison with the direct-field configuration data in Fig. 3A indicates a somewhat increased ion flux in the plume for the cusp-field case.

The current utilization ratio in Table I is useful in determining how effectively the applied magnetic field suppresses electron transport to the anode. Holding all other parameters constant, thruster efficiency will decrease with increasing electron current [13]. The high current utilization in the direct-field configuration almost certainly implies that electron transport is lowest in that case, leading to the conclusion that the thrust efficiency is higher for this configuration than in the cusp-field case.

The thrust, anode efficiency, and anode I_{sp} all generally increase with increasing discharge power. Anode flow rate, on the other hand, appears to have very little influence on the measured performance. Comparisons to performance values previously obtained for a 3-cm PPPL CHT [6] that employed electromagnet coils show that at 150 W the I_{sp} and efficiency in the permanent magnet thruster are both lower than those measured in the electromagnet thruster (I_{sp} and anode efficiency reduced from ~1400 s to ~1000 s and 26% to 16%, respectively). It should be noted that the anode efficiency on the 3-cm CHT does not account for the electrical power invested in the production of the magnetic field.

VI. CONCLUSIONS

Conventional (annular) Hall thrusters are efficient in the kilowatt power regime, but become inefficient at small sizes as the insulator surface area to discharge chamber volume ratio increases, leading to a commensurate increase in plasma wall losses. The CHT geometry eliminates the inner discharge channel surface and has a non-traditional magnetic field topology, giving it a lower insulator surface area to discharge chamber volume ratio and the promise of improved performance in the low power regime. This promise has in the past been demonstrated in a series of CHT designs that employed electromagnets to generate the magnetic field topology in the thruster.

In the present work, preliminary measurements were obtained on a 2.6-cm PPPL CHT that used permanent magnets to generate the applied magnetic field in the thruster. The use of permanent magnets promises even lower thruster power consumption by eliminating the electromagnet power sink. While ion flux in the plume was somewhat

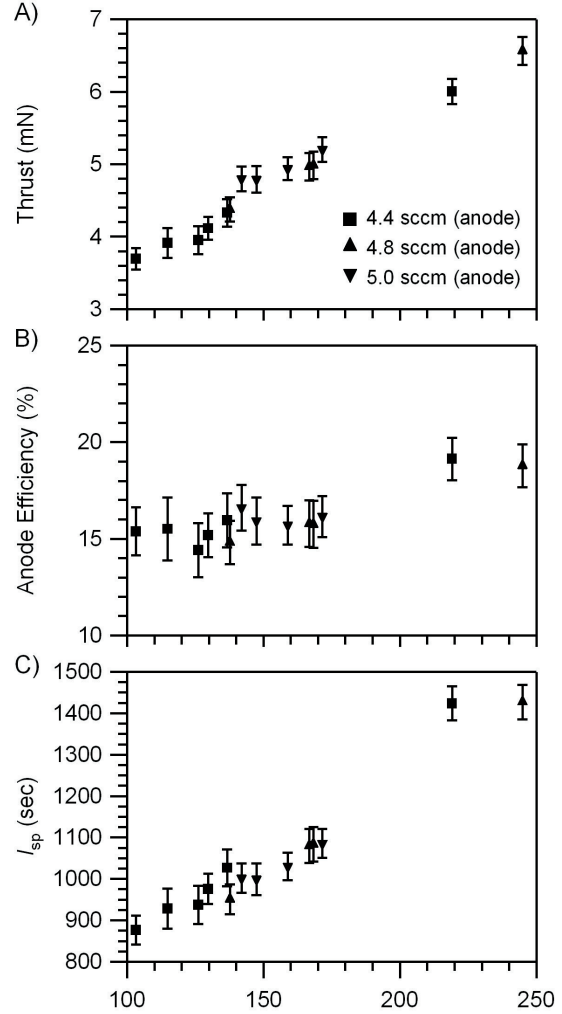


FIG. 4: Performance measurements for the CHT direct-field configuration: A) thrust, B) anode efficiency, and C) I_{sp} as a function of discharge power. Error bars represent a 95% (2σ) confidence interval.

higher for the cusp magnetic field configuration, the current utilization ratio was highest for the direct-field case, indicating it would have a higher efficiency.

Performance measurements on the direct-field magnet configuration thruster over a discharge power level ranging from 100-250 W were performed using the MSFC VAHPER thrust stand. The thruster produced thrust levels ranging from 3.5-6.5 mN, anode efficiencies spanning 14-19%, and I_{sp} between 875-1425 s. All performance parameters generally increased with discharge power and did not appear to be a strong function of anode mass flow rate. The current drawn by the thruster at a given discharge voltage level in testing at MSFC was significantly greater than that drawn in testing at PPPL. In addition, the magnetic field in the MSFC performance testing was reduced relative to the PPPL testing due to 'overheating' of the magnets.

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